

# Application of Inverse Method to Blended-Wing-Body Airplane Design(**逆解法による 翼胴一体型航空機の設計**)

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## 論文内容要旨

After the successful flight of the 'Wright Flyer' in 1903, many different kinds of airplanes have been designed by the aeronautical engineers. The need of faster and more powerful military airplanes has speeded up the development of the airplanes and its technologies. The design engineers seek an airplane configuration, which could lead to better performances. Researchers develop new theories and improve the existing ones. Several design tools have also been developed. All efforts are performed to have more efficient airplanes and to meet the changing demand in everyday life.

Nowadays airplanes are parts of everyday life. The use of the airplanes may be found in passenger's and cargo's transportations and military applications. Today's modern airplanes such as Boeing and Airbus are developed based on experience, years of experiment and technical achievement of many years. Most of these airplanes use the conventional configuration, which is characterized by cylindrical fuselage, wing and tail.

Aerodynamically, the figure of merit of an airplane performance can be indicated by Lift to Drag ratio ( $L/D$ ). Airplanes are designed to have  $L/D$  value as large as possible. Since the lift is fixed based on the airplane weight, the most efficient way to achieve large  $L/D$  is by designing the airplane with drag as small as possible. Many experiments and theoretical analysis have been performed to design the wing with large value of  $L/D$ . In the early days after the first flight of the Wright brothers, performance improvements are mainly achieved by involving the streamlining to reduce the drag and increasing the engine power to increase the speed. Furthermore, after more experimental data and theories become available then further effort can be done to increase the  $L/D$  value, in which wing/airfoil design plays an important role.

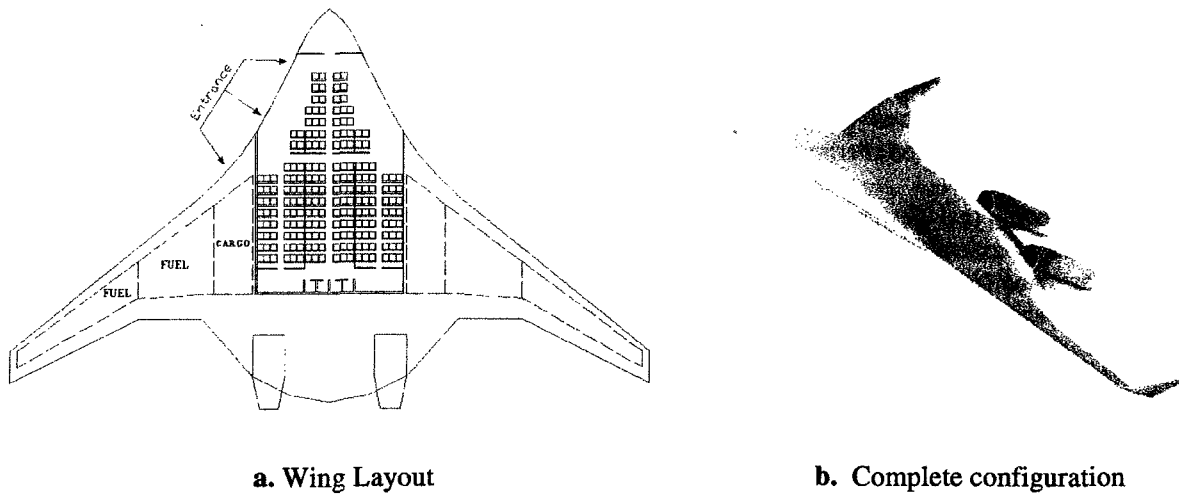
The value of  $L/D$  depends not only on the choice of the airfoil but it depends also on the wing planform and the complete airplane configuration as a whole system. One of the design concepts to achieve higher  $L/D$  value is the 'flying wing' configuration. The applications of the flying wing concepts were so far only for sport and military airplanes. The flying wing concept for the civil transport airplane has not been built or still only in the drawing table. The only flying wing airplane, which achieved operational development is the Bomber Northrop Grumman B-2.

Blended-Wing-Body (BWB) airplane, which basically is a flying wing configuration, is regarded as an alternate configuration to reduce drag and structural weight. Since BWB possesses no fuselage it may have smaller wetted area than the conventional airplane. In the conventional airplane the primary function of the wing is to produce the lift force. In the BWB configuration the wing has to carry the payload and to provide the necessary stability and control as well as to produce the lift. The fuselage has to create lift without much penalty on the drag. At the same time the fuselage has to keep the cabin size comfortable for passengers. Other advantage of BWB is a lower wetted area to volume ratio. Theoretically the lower wetted area will reduce drag and also increase the maximum lift to drag ratio. Higher value of  $L/D$  means that for

similar fuel weight, payload, speed and empty weight the flying wing configuration gains more distance range. When the airfoil has sufficient thickness then it is possible to distribute the mass within the wing more efficiently, which results in reduction of empty weight. This is a result of the reduction of structure weight to carry the bending moment. Furthermore BWB has lower wing loading than the one of the conventional airplane that reduces the takeoff distance. This last aspect is important and attractive for a medium size airplane.

The main objective of this research is to establish the required aerodynamic design tools for a Blended-Wing-Body airplane. The main design tool will be the Takanashi's inverse method. A target pressure specification technique and a surface modelling technique are incorporated to add the practical usefulness of Takanashi's inverse method. The other objective is to apply the Blended-Wing-Body concept to medium size airplane.

To design the BWB airplane there are several design aspects that should be taken into consideration. First for the stability reason the center of gravity location should be ahead of the aerodynamic center. This requirement can be achieved if the wing has enough sweep angle to shift the aerodynamic center backward. This will create space ahead of the aerodynamic center and therefore shifts the center of gravity to forward position. Furthermore it is preferable to have elliptical span loading distribution to reduce the induce drag. Second, to reduce the pitching moment due to engine thrust, it is preferable to place the engine buried above the wing. This configuration will have small wetted area, reduces the noise and prevents debris from entering the engines. Other consideration includes the required space to provide enough comfort for the passengers and emergency evacuation. There are only 2 entrances available for the passengers on each sides, however because the passenger cabin is short the loading, unloading and evacuation process will be fast enough. The BWB airplane has longer wingspan than the conventional airplane. The wingspan should be designed in such that it still fit into the small airport. The design configuration for 200 passengers is shown in figure 1.



**Figure 1.** Design configuration for 200 passengers

A design system is required to realize the wing. The inverse method is chosen as the main design tool. In the present study the Takanashi's inverse method, which is based on the '*residual-correction*' method, is utilized. The inverse design process starts with the specification of the target pressure distribution. The pressure difference between the initial and the target forms an input of the inversely formulated transonic small perturbation equations. The solutions of the equations provide the geometry's correction  $\Delta f$ , which are used to modify the initial geometry to form a new geometry. The flow solutions of this new shape may be obtained by applying the Navier-Stokes equations. If, after having checked the convergence, the design requirements are not satisfied, the design cycle is repeated with the new geometry as the replaced initial geometry. The process is repeated until the pressure different is minimized.

The most important and difficult aspect of utilizing the inverse method is the specification of the target pressure. To realize the flow constraints and the space requirement, it requires a method to specify the target pressure distribution, which will lead to both requirements. To solve this problem a constrained target pressure specification technique as proposed by Campbell is utilized. To manipulate the pressure distribution during the design process, the pressure distribution is divided into several regions bounded by several control points. The location of the control points and their pressure levels are obtained by using two approaches, *empirical estimation approach* and *control point fitting approach*.

In empirical estimation approach the controls points are developed by using empirically derived equations. Control point fitting approach is very useful to design target pressure distribution based on the existing airfoil, so the aim of this approach is to modify the existing pressure distribution.

In the control point fitting approach, the control points are initially fitted into the existing pressure distribution. Then the pressure level at every control point is modified using the equations from empirical estimation approach. During the iteration process the pressure level of the control points can be modified iteratively.

Because the BWB configuration has thick inboard wing and thin outboard wing, the blending of thick inboard wing into the thin outboard wing will be quite difficult to be realized by the linear lofting method. Therefore another method of surface modelling is required to create smooth curved surface. The curved-surface modelling becomes more important for the medium-size BWB airplane because of the abrupt change from the inboard to outboard wings. To achieve the smooth wing surface, in this study RAPID(Rapid Airplane Parametric Input Design) method is employed. RAPID methodology generates the smooth surfaces by solving the fourth order differential equation

The study shows that the proposed design system work well for BWB configuration. Although the Takanashi's inverse equations are based on small perturbation equations it can be used along with any flow solver regardless the type of the flow simulation. Typically to achieve the prescribed target pressure distribution requires 20 iterations. However the total required number of iterations could be much higher because during the design process the target pressure distribution is modified iteratively to achieve the design goals, which are the aerodynamic performance and the geometric constraint. RAPID method provides more flexibility in creating various wing planforms with curved surfaces than the linear lofting. Linear lofting method is simple and a good method for creating surfaces of straight tapered wing as commonly found in the conventional airplane.

Two conceptual designs of airplanes using BWB concept have been conducted. One is a regional airplane for 224 passengers with range up to 2500 nm at cruise speed of Mach number 0.8. The other is a commuter airplane for 52 passengers with the range up to 1200 nm at cruise speed of Mach number 0.5. The present results show that the BWB airplane has low wing loading, which may reduce the takeoff field length. The takeoff distance will also depend on the flight control system.

The present results are greatly encouraging. The value of lift to drag ratio of the medium size BWB seems to be reasonable enough. With its elliptical span loading the present value of lift to drag ratio is 19.3, although this will decrease when the engines are integrated. The elliptical span loading contributed to increase the lift to drag ratio by a factor of 2.6%. The wetted area is larger than the conventional airplane, however this gives more space for the passenger and larger wing area for having low wing loading. The present results indicate that the designed airplane requires Stability Augmentation System (SAS). This is based on the fact that at the estimated center gravity location the airplane has positive  $C_{m_{\alpha}}$ , which is unstable. The present results also indicate that to achieve a short takeoff distance the designed airplane requires less maximum lift coefficient than the conventional airplane of the same payload. For example for a takeoff distance of 1600 m it requires maximum lift coefficient of 1.7. For comparison Airbus A320 with the takeoff distance of 2100 m has maximum lift coefficient around 3.

To apply the BWB concept for smaller airplane such as for 50 passengers is very difficult. The present result shows that the value of lift to drag ratio is very low for this configuration. It is difficult to achieve higher value of lift to drag ratio, this may be caused by the use of thick airfoils and/or incorrect design of pressure distribution. Also it is more difficult to create accessible space (e.g. cargo hold) without increasing the wetted area and wing thickness. Thus the only gain of utilizing the BWB concept for small airplane probably is its lower wing loading.

# 審査結果の要旨

遷音速旅客機は半世紀に渡って着実に性能改善がなされてきたが、円筒形胴体に主翼と尾翼をつけた機体形状には大きな変化がなかった。しかし、経済性や環境適合性に対する近年の更なる改善要求から、革新的な機体形状の研究が世界的に行われている。超大型機を目指した翼胴一体形状や環境に適合した範囲内での高速化を狙ったソニック・クルーザー等である。これら革新的機体形状の創成には古典的経験的な設計手段だけでは困難である。一方、過去の空力設計に無かった技術として数値流体力学があり、その活用が革新的機体形状創成には不可欠とされている。本研究では、数値流体力学による空力解析と逆解法による形状設計法とを組合せ、曲面を多用した機体空力形状を設計する手法を構築し、かつその手法により翼胴一体形状を用いた中型旅客機の空力設計を行った。本論文は、この研究成果についてまとめたもので、全編6章よりなる。

第1章は序論であり、本研究の背景および目的を述べている。

第2章では、要求圧力分布を実現する形状を得るための逆解法について、高梨の逆解法に目的圧力分布指定法と曲面定義法とを取り入れた設計法について詳述している。これにより、数学的境界条件が多くなるために制約条件までを満たす解を得る事が困難といわれていた逆解法に大きな有用性を与えた。また、翼胴一体型航空機に不可欠な厳しい制約条件下での曲面を多用した空力形状を設計する手法を構築した。これは、今後の革新的航空機の空力設計手法として非常に重要な技術である。

第3章では、翼厚比の大きな遷音速翼型設計に第2章で開発した設計手法を適用した結果について述べている。翼胴一体形状では、翼の中に客席を確保するために厚い翼型が必要であり、一方では遷音速飛行での衝撃波損失を最小にするには薄い翼型が有利である。この相反する要求を満たす遷音速翼型の設計を、幾何学的制約条件内で要求性能を導く圧力指定法により可能であることを示した。このことは翼胴一体型機体の空力設計を行う上で貴重な成果である。

第4章では、第2、3章において開発された設計手法を用い、中型の翼胴一体型機体の概念設計および空力設計を行った結果について記述している。翼胴一体型は、超大型機においては空力性能を大幅に改善することが知られているが、乗客200名程度の中型機については空力設計の困難さから未開拓であった。しかし、本研究により空力的な性能が十分に確保できることが示されるとともに、翼胴一体型の低翼面荷重により短距離離着陸性能が得られる等の利点を示した。中型サイズでの翼胴一体型機体の空力設計は世界的にも初めてのことであり、その有効性が確認されたのは非常に重要な研究成果である。

第5章では、我が国およびアジア諸国で需要が見込まれる50人程度の小型旅客機に翼胴一体型形状が適用できるかを調べている。その結果、巡航時の空力性能では既存機に対して優位性を得ることは困難であること、飛行安定性を得ることも難しさが残ることが示された。しかし、離着陸性能や空港騒音での利点から利便性と環境適合性に優れた航空機になる可能性を示唆している。小型機における翼胴一体型の特性を明らかにしたことは、今後の革新的航空機開発に貴重な情報を提供した研究成果である。

第6章は結論である。

以上要するに本論文は、数値流体力学と逆解法および圧力指定法や曲面定義法の有機的連携により革新的航空機形状の空力設計手法を構築し、かつ翼胴一体形状による中型旅客機の有効性を示したもので、航空工学および数値流体力学の発展に寄与するところが少なくない。

よって、本論文は博士（工学）の学位論文として合格と認める。